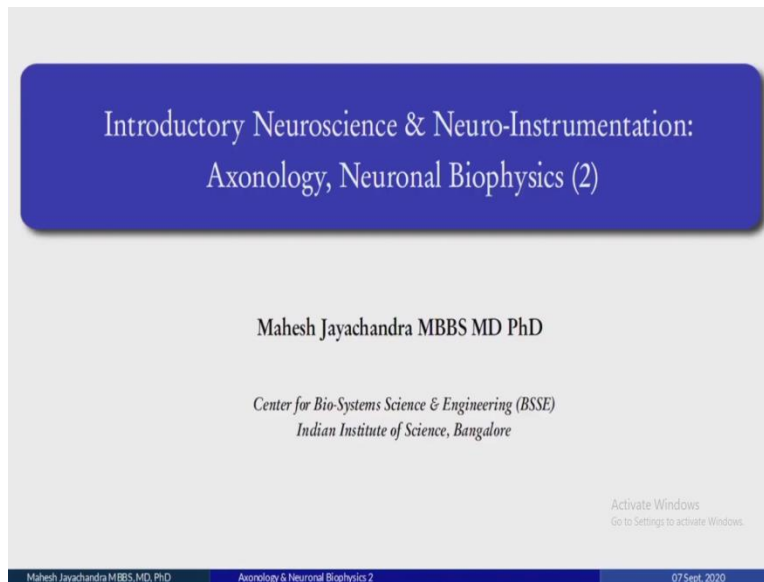


**Introduction to Neuroscience & Neuro-Instrumentation**  
**Professor. Mahesh Jayachandra MBBS MD PhD**  
**Center for Bio-Systems Science & Engineering**  
**Indian Institute of Technology, Bangalore**  
**Lecture No. 14**  
**Introductory Neuroscience & Neuro-Instrumentation:**  
**Axonology, Neuronal Biophysics (2)**

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So, introductory neuroscience and neuro-instrumentation: axonology and neuronal biophysics, part two.

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### Electrotonic Spread Depends on the Characteristic Length ( $\lambda$ )

Consider the spread of electrotonic potential under steady-state conditions (C). In standard cable theory, this is

$$V = \frac{r_m}{r_i} \cdot \frac{d^2V}{dx^2}.$$

The steady-state solution of this equation for an infinite cable, for positive values of  $x$  gives,

$$V = V_0 e^{-x/\lambda}$$

Here lambda ( $\lambda$ ) is defined as the square root of  $r_m/r_i$  (in cm), and,  $V_0$  is the value of  $V$  at  $x = 0$ .

LENGTH CONSTANT

$$\lambda = \sqrt{\frac{r_m}{r_i}}$$

RESISTANCE OF NEURON MEMBRANE

INTERNAL NEURON RESISTANCE

when  $x = \lambda$ , the ratio of  $V$  to  $V_0$  is  $e^{-1} = 1/e = 0.37$

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So, we were talking about the passive spread or electrotonic spread of potentials across dendrites, across axons. And this depends on something called the characteristic length or Lambda. So, consider the spread of electrotonic potential under steady-state conditions. In standard cable theory, this equation defines it where  $V$  is voltage, then you have the, a term for membrane resistance, you have a term for internal resistance and this is  $d^2v/dx^2$  is its spread over the length of the axon, the spread of the voltage length of the axon.

So, the steady-state solution for this equation in an infinite cable for positive values of  $x$  gives

$$V = V_0 e^{-x/\lambda}$$

And here, this is very straight forward to derive from cable theory. And here, this term Lambda is defined, it is defined as the  $\sqrt{r_m/r_i}$ . So, the resistance of the membrane, neuronal membrane, is divided by the internal resistance of the neuron. And  $V_0$  is the value of  $v$  at  $X=0$ . So, when  $x = \lambda$ , the ratio of  $V$  to  $V_0 e^{-1/\lambda}$  or  $1/e$  or  $0.37$ . So, it reaches  $0.37$  of its original value, where  $x=\lambda$ .

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## Characteristic Length ( $\lambda$ )

Thus, lambda  $\lambda$  is a critical parameter defining the length over which the electrotonic potential decays to a value of 0.37 of the value at the site of the input.

It is referred to as the characteristic length ( $\lambda$ , space constant, length constant) of the cable.

$$\lambda = \sqrt{\frac{r_m}{r_i}}$$

Diagram labels:   
 - LENGTH CONSTANT (pointing to  $\lambda$ )   
 - RESISTANCE OF NEURON MEMBRANE (pointing to  $r_m$ )   
 - INTERNAL NEURON RESISTANCE (pointing to  $r_i$ )

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So, therefore, Lambda is a critical parameter defining the length over which the electrotonic potential decays through a value of 0.37 from the original value at the site of input. So, this is referred to as lambda, it is also referred to as characteristic length, it is referred to as space length or it is referred to as the length constant of the cable.

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## Length/Space constant ( $\lambda$ ) and Specific Membrane Resistance ( $R_m$ )

The higher the specific membrane resistance ( $R_m$ )

→ the higher the value of  $r_m$  for that segment

→ the larger the value for  $\lambda$

→ and the greater the spread of electrotonic potential

$$\lambda = \sqrt{\frac{r_m}{r_i}}$$

Diagram labels:   
 - LENGTH CONSTANT (pointing to  $\lambda$ )   
 - RESISTANCE OF NEURON MEMBRANE (pointing to  $r_m$ )   
 - INTERNAL NEURON RESISTANCE (pointing to  $r_i$ )

Specific membrane resistance ( $R_m$ ) is thus an important variable in determining the spread of activity in a neuron.

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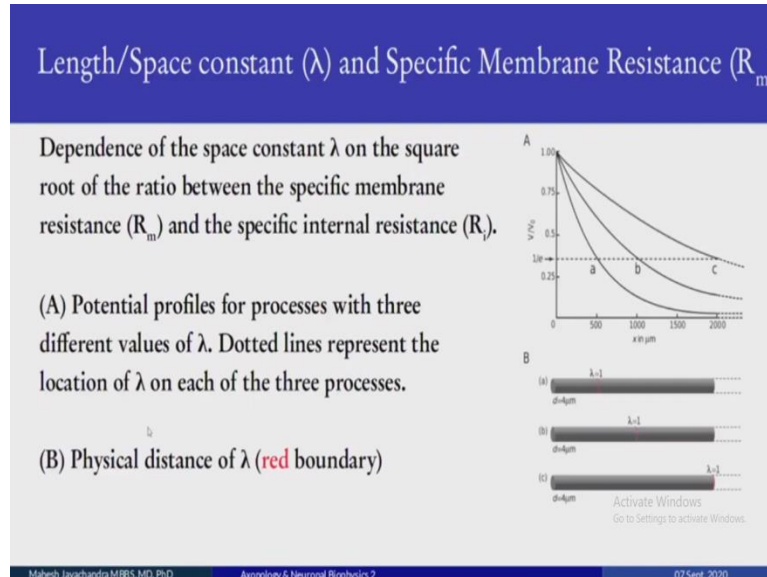
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So, the higher the specific membrane resistance, capital  $R_m$  leads to a higher value of  $r_m$  for the segment, which is the resistance of a patch of membrane. So, therefore the value of Lambda is bigger and so the electrotonic spread, potential spreads more. So thus, specific membrane

resistance capital  $R_m$  is an important variable in determining the spread of activity, this passage electrical activity in a neuron.

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So, length and space constant and membrane resistance. So consider, you know, an axon, 3 axons with 3 different values of lambda, this is Lambda of the first, this curve, this is the second, this curve and this is the third, this curve. So, the potential profiles for all these different values are on top over here and the dotted lines represent the location of lambda on each of these processes, the physical distance is shown in red. So in the first case, because of the properties, it is only so much, in the second case it is much more and in the third case, it is even more.

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**Lambda ( $\lambda$ ): Some Numbers**

$R_m$  can vary from values of less than  $1000 \Omega\text{cm}^2$  to more than  $100,000 \Omega\text{cm}^2$  in different neurons and in different parts of a neuron.

*Note: Lambda ( $\lambda$ ) varies with the square root of  $R_m$ , so a 100-fold difference in  $R_m$  translates into only a 10-fold difference in  $\lambda$ .*

Conversely, the higher the value of the specific internal resistance ( $R_i$ ), the higher the value of  $r_i$  for that segment, the smaller the value of  $\lambda$ , and the less the spread of electrotonic potential through that segment.

The value of  $R_i$  is in the range of approximately  $50\text{--}100 \Omega\text{cm}$  in muscle cells and the squid axon. In mammalian neurons, it is about  $200 \Omega\text{cm}$ .

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So  $R_m$ , some numbers  $R_m$  can vary in values from less than 1 k ohm centimeter square to more than a 100 thousand ohm square centimeter in different neurons and different parts of a neuron. So note, that lambda varies with the  $\sqrt{R_m}$ . So, a 100 fold difference in  $R_m$  translates to only a tenfold difference in lambda. Conversely, a higher value of specific internal resistance  $R_i$ , so the higher the internal resistance,  $r_i$ , for that segment the smaller the lambda and the less the spread of the potential through the segment.

Because the resistance prevents the electric current from spreading. So, the value of  $R_i$  is approximately in the range of 50 to 100-ohm centimeter muscle cells and squid axon. In mammalian axons, you know, in mammalian neurons, it is much higher, about 200-ohm centimeter.

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Final  $\lambda$  thoughts

This limited range suggests that  $R_i$  is less important than  $R_m$  in controlling passive current spread in a neuron.

Furthermore, the square-root relation further reduces the sensitivity of  $\lambda$  to  $R_i$ .

Caveats:

1. Membranous and filamentous organelles in the cytoplasm may alter the effective  $R_i$
2. The relative significance of  $R_i$  and  $R_m$  depends greatly on the length of a given process

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So, this kind of limited range suggests that  $R_i$  is less important than  $R_m$  in controlling the passive of current spread in the neuron i the internal resistance of an axon is not so important as the membrane resistance of the axon, as far as the passive spread of electronic spread of electrical activity in the neuron. Furthermore, it is a square root relationship. So, it further reduces the sensitivity of  $\lambda$  to  $R_i$ . However, there are some caveats.

So, in the cytoplasm, you have membranous and filamentous organelles, tubules, various things mitochondria, endoplasmic reticulum, which we looked at in the microscopic anatomy of the central nervous system. All these may change the effective  $R_i$  and also the relative significance of  $R_i$  and  $R_m$  depends on the length of the given processes and how branched it is and so forth.

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**Electrotonic Spread Depends on the Diameter of a Process**

The space constant  $\lambda$  depends not only on the internal and membrane resistance, but also on the diameter of a process. Thus, from the relations between  $r_m$  and  $R_m$ , and  $r_i$  and  $R_i$ , discussed in the previous slides,

$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$

Neuronal processes vary widely in diameter. The thinnest processes are the distal branches of dendrites and the necks of dendritic spines. These processes may have diameters of  $>0.1 \mu$ .

Note, again, that the relation to  $\lambda$  is the square root – a 10-fold difference in diameter increases  $\lambda$  by only 3-fold

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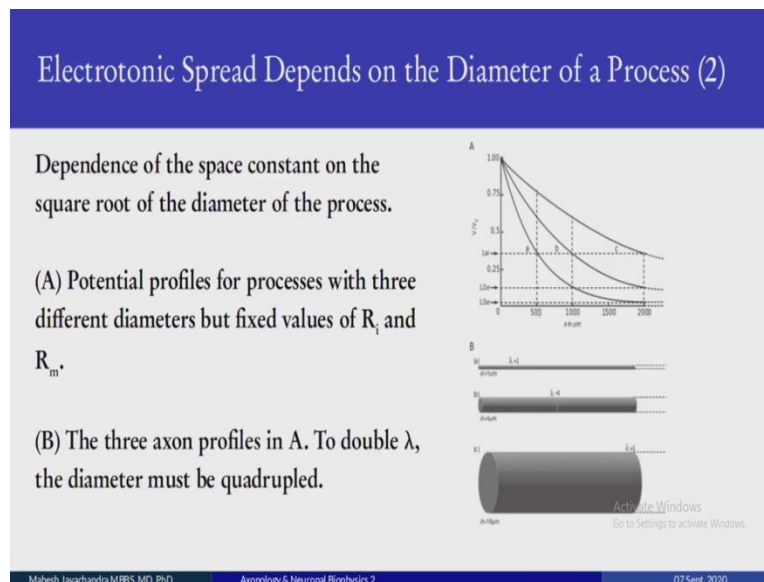
So, the space constant also depends on the diameter of the process besides the resistance which we considered before. So, thus from the relationships of  $r_m$  and  $R_m$ ,  $r_i$  and  $R_i$ , discussed in the previous slides you can,

$$\lambda = R_m / R_i$$

and that reduces to the square root of the specific membrane resistance, specific internal resistance, and the  $d/4$  is the, a term for the cross-sectional area.

So, neuronal processes vary very widely in diameter. The thinnest processes are the distal branches of dendrites and the necks of dendritic spines. These have diameters of greater or equal to  $0.1 \mu$ . Note again, that the relationship of  $\lambda$  is to the square root. So, a tenfold difference in diameter increases  $\lambda$  by only 3 times.

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So here, we have the relationship of lambda to diameter. So again, you have 3 different axons with 3 different diameters 1  $\mu$ m, 4  $\mu$ m, and 16  $\mu$ m. And you see the potential profile, so lambda in the first one is over here, in the second one is here and the third one is here because you know, it spreads much further because its cross-sectional area is much more. So the 3, to double lambda, the diameter must be quadrupled.

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### Electrotonic length (L)

The real length of the giant axon is several centimeters. To relate real length to characteristic length, we define Electrotonic length (L), of a cylindrical neurite as its physical length divided by its space constant,

$$L = x/\lambda$$

Thus, if  $x = 30$  mm, then  $L = 30 \text{ mm}/4.5 \text{ mm} = 7$ .

The electrotonic potential decays to a small percentage of the original value by only three characteristic lengths.

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So, the real length of a giant axon is several centimeters. So, to relate this real length to the characteristic length or lambda, we define electrotonic length or L of a cylindrical neurite as its



physical length divided by its space constant. So thus, if  $x$  is 30 millimeters, then  $L$  would be, that is the electrotonic length  $30/4.5 = 7$ . So, the electrotonic potential decays to a small percentage of the original value by 3 characteristic lengths. So, this has implications when stimulating a nerve.

So, you can stimulate a nerve and for whatever reason, experimental conditions, you know, it goes down, it can move by 3 characteristic lengths and then you have a brand new zone to stimulate and the previous area does not affect the new stimulatory site.

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The slide has a blue header with the title "Electrotonic length (L)". The main content area is light gray and contains three paragraphs of text. The first paragraph states that dendritic branches have lengths much shorter than three characteristic lengths. The second paragraph explains that in dendrites, branching patterns dominate the extent of potential spread. The third paragraph notes that action potentials overcome the attenuation of passively spreading potentials over axon length, specifically applying to long axons and their collaterals. A video of a man with glasses and a beard speaking is overlaid on the right side of the slide. At the bottom, there is a blue footer bar with the text "Mahesh Jayachandran MBBS, MD, PhD" and "Axonology & Neuronal Biophysics 2".

Electrotonic length (L)

By contrast, dendritic branches have lengths that are usually much shorter than three characteristic lengths.

In dendrites, therefore, the branching patterns dominate the extent of potential spread.

Action potentials overcome the attenuation of passively spreading potentials that occur over the axon length - *applies to the long axons, not to shorter axons and their collaterals.*

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But these were axons that we discussed so far. If you look at dendrites, they have lengths that are very much shorter in size than axonal lengths and characteristic lengths. So, therefore in dendrites, what is important is the branching patterns, you know, which modulate the extent of potential spread. So, action potentials overcome the attenuation of passively spreading potentials that occur over axon length. But this occurs to long axons, not too short axons and their collateral.

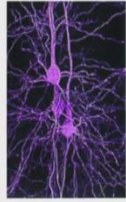
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## Electrotonic length (L)

Combined Analog and Digital signaling:  
Excitatory synaptic potentials in the soma may spread through the axon to reach terminal boutons onto nearby cells.

The variable amount of synaptic depolarization thus acts as an analog signal to modify the digital signaling carried by the axonal action potentials.

This mechanism has been shown in layer 5 pyramidal neurons in the neocortex.



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So, putting all this together, we have combined analog and digital signaling in neurons. So, you have the pyramidal cells over here on the right, couple of them, and you have their extensive dendritic branches and you would have from the base, these cells axons leading onto other cells-one over here, one over here and there is one behind actually 3 of them over there. So, you have excitatory synaptic sites on the soma and they get inputs from different cells, different networks, and, depending on the amount of excitation, the amount of inhibition, they modify the analog signals.

The analog signals reach a threshold. Once it reaches a threshold, you have action potentials that are kind of digital, all or nothing, and coded by frequency. So, these mechanisms are seen in, have been found in pyramidal cells. So again, so you, think of analog computer over here, analog computation occurring in the dendritic branches and this modulates action potentials coming out from the digital neurons. So, a single cell is a combined analog and a digital supercomputer.

(Refer Slide Time: 10:30)

## How do the electrotonic properties affect spread of fast signals?

Many neural signals change rapidly. In mammals, fast action potentials characteristically last from 1 to 5 ms, and fast synaptic potentials last from 5 to 30 ms.

Rapid signal spread depends not only on all the factors discussed thus far, but also on the membrane capacitance ( $c_m$ ), which is due to the lipid part of the cell membrane.

Classically, the value of the specific membrane capacitance ( $C_m$ ) =  $1 \mu\text{F}/\text{cm}^2$

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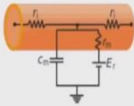
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So fast signals, so how do electrotonic properties affect the spread of fast signals? So, many neural signals change rapidly. So, in mammals, you have fast action potentials that last from 1 to 5 milliseconds. And fast synaptic potentials that last from 5 to 30 milliseconds. So, rapid signal spread depends not only on all these factors discussed so far but also on the membrane capacitance because when there is a rapid change, capacitative effects come into play.

And of course, to remind you, the capacitance is due to the lipid part or the lipid moiety of the cell membrane. And classically, we put the value of specific membrane capacitance,  $C_m$  as 1 microfarad per centimeter square.

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### Electrotonic properties and spread of fast signals (2)



In the equivalent electrical circuit for a neural process, the membrane capacitance is placed in parallel with ohmic components of the membrane conductance and the driving potentials for ion flows through those conductances.

Neglecting the resting membrane potential, we inject a current step into a soma.

The time course of the current spread to ground is described by the sum of the capacitive and resistive current (plus the input current,  $I_{\text{pulse}}$ ):

$$C \frac{dV_m}{dt} + \frac{V_m}{R} = I_{\text{pulse}}$$

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So, continuing with electrotonic properties and the spread of fast signals. So, here you have the equivalent circuit of the renewal process. The membrane capacitance is in parallel with the ohmic components of the membrane conductance the electromotive force and the driving potential. And neglecting the resting membrane potential, what we do is, we inject current into a cell body. So, the time course of the spread of current is described by two currents one is the capacitive current, the part which discharges and recharges the membrane, and the resistive current plus of course the input current which you give during the pulse.

So, this would describe it, the capacitance. Then you have a resting membrane potential that changes. Then you have a membrane potential and then you have the resistance and that is equal to the current pulse.

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### Time Constant $\tau$

Rearranging,  
*where  $RC = \tau$  ( $\tau$  is the time constant of the membrane).*

$$C \frac{dV_m}{dt} + \frac{V_m}{R} = I_{\text{pulse}} \quad \quad RC \frac{dV_m}{dt} + V_m = I_{\text{pulse}} \cdot R$$

The solution of this equation for the response to a step change in current (I) is,

$$V_m(T) = I_{\text{pulse}} R (1 - e^{-T})$$

where  $T = \tau/t$ . When the pulse is terminated, the decay of the initial potential ( $V_0$ ) to rest is given by,

$$V_m(T) = V_0 e^{-T}.$$

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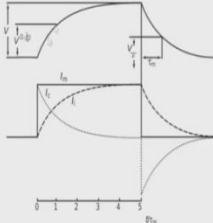
So if we rearrange this, and we substitute  $RC = \tau$  which is the time constant of the membrane, we get this by rearranging, we get this. And the solution for this equation for a response to a step current change in potential is given by this equation where  $T = \tau/t$ . When the pulse is terminated, the decay of the initial potential to rest is given by this equation. So, it comes back to baseline and again you see  $e$  and  $e^{-t}$ .

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### Time Constant $\tau$

These “on” and “off” transients shown in the time required for the voltage change across the membrane to reach  $1/e = 0.37$  of its final value.

*It is analogous to the way that the length constant defines the spread of voltage change over distance.*



The equivalent circuit of a single isolated compartment responds to an injected current step by charging and discharging along a time course determined by the time constant,  $\tau$ .

$V$  = steady-state voltage  
 $I_m$  = injected current applied to membrane  
 $I_c$  = current through the capacitance  
 $I_l$  = current through the ionic leak conductance  
 $\tau_m$  = membrane time constant

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So, what happens? So you have an "on" transient and then you have an "off" transient. This is how it looks. You have a step current coming in here and it takes some time for the membrane capacitance to discharge, recharge, to reach that thing. And when you switch it off, this is a square pulse. It again decays back to normal. So, the on and off transient shown in the time required for the voltage change across the membrane to reach  $1/e$  of its final value which is 0.37. So, this is similar to the way the length constant defines the spread of voltage over distance.

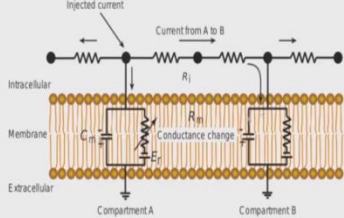
So, the equivalent circuit of a single isolated compartment responds to an injected step current by charging and discharging along a time course determined by the time constant  $\tau$ . And we, for this figure,  $V$  is a steady-state voltage.  $I_m$  is the injected current applied to the membrane, just an electrical square pulse on top of the axon.  $I_c$  is a current through the capacitance.  $I_i$  is the current through the ionic leak conductance. And  $\tau$  is the membrane time constant.

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### A 2-Compartment Model Defines Basic Signal Spread (1)

These spatial and temporal cable properties can be combined in a two-compartment model that can be applied to the generation and spread of any arbitrary transient signal.

In the simplest case, positive charge injected into compartment A attempts to flow outward across the membrane, partially opposing the negative charge on the inside of the lipid membrane (the charge responsible for the negative resting potential), thereby depolarizing the membrane capacitance ( $C_m$ ) at that site.



The diagram illustrates a two-compartment model of a neuron. It shows two compartments, A and B, separated by a membrane. The intracellular space is represented by a series of resistors. The membrane is represented by a series of capacitors ( $C_m$ ) and a conductance change ( $G$ ). The extracellular space is represented by a series of resistors. An injected current is shown entering compartment A. The diagram also shows the flow of current from A to B through the membrane.

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So, consider a two-compartment model. So you have two compartments, there is one compartment here and there is one compartment here. This is compartment A and this compartment B. So in compartment A, you have its equivalent circuit, you have the capacitive term and you have the resistive and the EMF term. Likewise, with B. So, this very simple two-compartment model can be applied to the generation spread of any arbitrary transient signal.

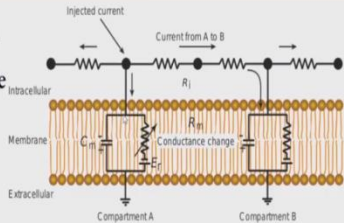
So, consider the simplest case. So, this is compartment A and you inject current, positive charge here. And this flows outward across the membrane, partially opposing the negative charge on the

inside of the lipid membrane. This negative charge is responsive to the resting membrane potential. And thereby, it depolarizes the membrane capacitance at this site.

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### A 2-Compartment Model Defines Basic Signal Spread (2)

At the same time, the charge begins to flow as current across the membrane through the resistance of the ionic membrane channels ( $R_m$ ) that are open at that site.



The proportion of charge divided between  $C_m$  and  $R_m$  determines the rate of charge of the membrane, i.e., the membrane time constant,  $\tau$ . The electrotonic current that spreads between the two segments is referred to as the local current.

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At the same time, the charge begins to flow as a current across the membrane through the resistance of the ionic membrane channels that are open in this site, across the membrane. And the proportion of charge divided between  $C_m$  and  $R_i$  determines the rate of charge of the membrane, which is the membrane constant. So, the electrotonic current which spreads from one compartment to another is also called the local current.



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## Impulses Propagate in Unmyelinated Axons by Local Currents

Here, the local current spreading through the internal resistance to the neighboring compartment enables the action potential to propagate along the membrane of the axon.

Each of the cable properties is relevant in specific ways:

- 1) For brief signals such as the action potential,  $C_m$  is critical in controlling the rate of change of the membrane potential.
- 2) For long processes such as axons,  $R_i$  increasingly opposes electrotonic current flow.

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So, in unmyelinated axons, if you remember, some axons have myelin insulating them, some of them are unmyelinated. In an unmyelinated axon, the local current spreading through the internal resistance allows the propagation to the next compartment. So, each of these cable properties is relevant in specific ways. So, for brief signals such as an action potential,  $C_m$  the capacitance is critical in controlling the rate of change of membrane potential. For long processes such as axon, the internal resistance is important because it opposes the electrotonic current flow.

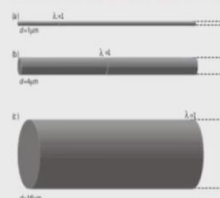
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## Impulse Propagation in Unmyelinated Axons (2)

Each of the cable properties is relevant in specific ways (contd.):

- 3) The effect of  $r_m$  decreases with increased membrane area (parallel current paths); this is greater in thinner axons, which have shorter  $\lambda$ .
- 4)  $R_m$  can vary widely. A high value of  $R_m$ , for example, forces current further along the membrane, increasing  $\lambda$  and the spread. However, it also increases  $\tau$ , thus slowing the response of a neighboring compartment to a rapid change.

Increasing the diameter of the axon lowers the effective internal resistance of a compartment, thereby also increasing the space constant ( $\lambda$ ), but without a concomitant effect on the time constant ( $\tau$ ).



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So continuing, the effect of  $r_m$ , you know, membrane resistance, decreases with increased membrane areas because of parallel current paths. This is greater in thinner axons that have a shorter  $\lambda$ . Specific resistance,  $R_m$ , can vary widely. So if it is high, then the current is forced to spread along the membrane, increasing  $\lambda$  and spread. However, at the same time,  $\tau$  is also increased, because if you remember,  $\tau = RC$ . Thus slowing the response of the neighboring compartment to this change.

So, consider what happens when you increase the diameter of an axon, it lowers, so here it is 1  $\mu$ m, 4  $\mu$ m, and 16  $\mu$ m. So, it lowers the effective internal resistance, thereby it increases the space constant  $\lambda$  but without an effect on the time constant  $\tau$ . So, these are the effects, cable properties are very important, they have very distinct effects on a local current and electrotonic spread of current in the dendritic trees.

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How to make axons conduct faster?

The evolution of larger brains to control larger bodies requires communication over longer distances.

So axons have to conduct impulses faster.

A direct way of increasing the rate of conduction is by increasing the diameter, but larger diameters mean fewer axons within a given space.

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So, the question is how do you make it conduct faster? Because once you have large brains, I mean large brains compared to you know, invertebrates. So, we need to control large bodies and that requires communications over long distances. Even though it feels very fast for us, thought and stuff, the maximum speeds of axonal conduction are only about 100 to 120 meters per second in humans. And much much slower in lower forms. So, there is this problem in evolution how do you make axons conduct faster?

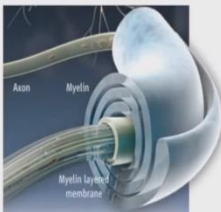
So one way to increase, you know, axonal conduction is to increase the diameter. But there is a limit, you know, you cannot have, the squid giant axon is probably the axon which we know with the maximum diameter. You cannot increase axon's diameters indefinitely because larger diameters mean fewer axons within a given space and fewer axons mean less cognitive processing.

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### Myelinated Axons Have Membrane Wrappings

Another way of increasing the rate of conduction is to make the kinetics of the impulse mechanism faster.

- Action potential in mammalian nerves are fast.
- Add more resistances in series with the membrane resistance, and more capacitances in series with the membrane capacitance (add as reciprocals).
- Done by *Schwann* cells (a glial cell) in the PNS and *Oligodendrocytes* in the CNS by wrapping their cell membranes around an axon (myelin).
- Myelinated nerves are the fastest in the CNS.



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So, coming back to myelin. So one way is to increase the rate of conduction, which is to make the kinetics of the impulse mechanism faster. So, if you remember, we talked about myelin, so now we will talk about biophysics. So, an action potential in the membrane, mammalian nerves are very fast. So, with the wrapping of these cell membranes from the oligodendrocytes and the Schwann cells, more resistances are added in the series of the membrane resistances. More capacitances are in series of the membrane capacitance, remember capacitance is added as reciprocals.

And this kind of insulates and forces, you know, faster conduction. We will get to it in just a bit. So, just to remind you, these myelin layers are provided by the Schwann cells in the peripheral nervous system and the oligodendrocytes in the central nervous system, they wrap their cell membranes on an axon. And because of this, they are the fastest, myelinated axons are fastest in the central nervous system.

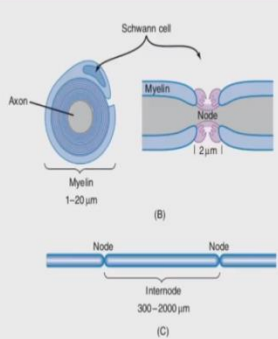
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### Myelinated Axons Have Booster Sites for Faster Conduction

Myelinated axons are not myelinated along their entire length. At regular intervals the myelin covering is interrupted by a node of *Ranvier*.

The density of voltage sensitive  $\text{Na}^+$  channels at the node is high ( $10,000 \mu/\text{m}^2$ ). It is very low ( $20 \mu/\text{m}^2$ ) in the internodal zone.

This difference in density means that the impulse actively is generated only at the node.



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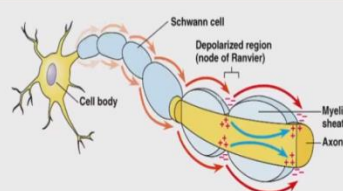
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So, myelinated axons are not myelinated across the entire length. If you remember, we have nodes, nodes of Ranvier, they are interrupted. So here you have a cross-section of an axon with the myelin layers and the Schwann cell over there. And here, you have the longitudinal section and here you see the node in between. So, the density of sodium channels in the node is very high, you know, about 10,000. It is much lower in the internodal regions. An internode is approximately 300  $\mu\text{m}$  to 2000  $\mu\text{m}$ . This difference in density means that most of the action potential happens at the nodes, not so much in the internodes.

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### Impulse conduction in Myelinated Axons

The impulse jumps from node to node, and the process therefore is called saltatory conduction. Myelinated axons resemble passive cables with active booster stations.



The Hursh factor (Hursh, 1939) states that the rate of propagation of an impulse along a myelinated axon in meters per second is six times the diameter of the axon in  $\mu$ . Largest axons in the CNS  $\sim 20 \mu\text{m}$  diameter; Conduction velocity (CV) is 120 m/sec. Thin myelinated axons are  $\sim 1 \mu\text{m}$ ; CV 5 - 10 m/sec.

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So, the impulse jumps from one node to another. And it is called saltatory conduction or leaping conduction. So, this makes it much faster. And myelinated axons, one way to think of it, resemble passive cables with active booster stations. And Hursh, in 1939, found an empirical law, that states that the rate of propagation of an impulse along a myelinated axon per second is 6 times the diameter of the axon in  $\mu\text{m}$ .

So, the largest neuron in the central nervous system are approximately 20  $\mu\text{m}$  in diameter and their conduction velocity is 120 meters per second. Thinly myelinated axons are approximately 1  $\mu\text{m}$  in diameter and their conduction velocity is only 5 to 10 meters per second. So, meters per second, very very slow compared to the transmission of electricity or light, very very slow.

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Myelination	
In rapidly conducting axons the impulse may extend over considerable lengths.	The impulse is generated <u>simultaneously</u> by many nodes (local currents activate adjacent nodes).
In a $20\mu\text{m}$ diameter axon conducting at 120 m/sec, at any instant of time an impulse of 1-ms duration extends over a 120 mm length of axon, which includes <u>more than 100 nodes of Ranvier.</u>	<u>For axons of equal cross-sectional area, myelination is estimated to increase the impulse conduction rate 100-fold.</u>
	At less than $1\mu\text{m}$ in diameter, there is an advantage, all other factors being equal, for an axon to be unmyelinated.

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So, some more thoughts about myelination. So, because of the saltatory conduction, the impulse, the length of the impulse, it may extend over a considerable length across the axon. So, for example, in a 20  $\mu\text{m}$  diameter axon conducting at 120 meters a second at any given time, an impulse of 1 millisecond, this is a typical action potential. It extends over a 120-millimeter length of axon which includes more than 100 nodes of Ranvier.

So, on action potential, even though it comes up like this and goes down, it extends over 100 nodes of Ranvier. So, this impulse is generated simultaneously by many nodes. The local currents activate adjacent nodes. So, for axons of equal cross-sectional area, they have

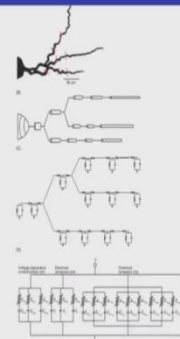
myelination, impulse conduction increases 100 fold. However, if the axon is less than 1  $\mu$ m in diameter, and all other factors are equal, there is an advantage for the axon to be unmyelinated.

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### Dendritic tree "Equivalent Cylinder"

Rules governing impedance have been worked out in the case where the sum of the daughter branch diameters raised to the 3/2 power is equal to that of the parent branch.

Here the system of branches is an equivalent cylinder, resembling a single continuous cable.



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So, with all these facts, how does current spread in a dendritic tree? So, the dendritic tree constitutes a conductance load on activity and these are the different kinds of the dendritic tree, what have it is literally like the different trees in a forest. So, the spread of activity from one side is determined by the impedance match or mismatch between that site and neighboring sites. This is electrical theory.

Consider your speakers, your speakers have a particular impedance. If you use the wrong impedance, the output will be, you know, distorted or less. So, this on the below is a compartment model of a Purkinje cell in the cerebellum, I think by (23:00) group. And the soma is just a round sphere, we are not interested in the soma. The action is over here, in the dendritic branches and if you would notice, they have different diameters. And as you go to the periphery, they become thinner and thinner. And all this is electrical compartment modeling. This is not real, this is a model. But you can see how detailed it can get.

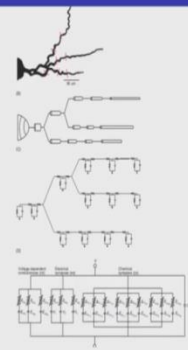
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### Modeling Dendritic Electrotonic potential spread

This provides a starting point in analyzing synaptic integration and “equivalent dendrites.”

Integration of synaptic potentials in passive dendrites is nonlinear because of interactions between the synaptic conductances.

The rules for electrotonic spread in dendrites are the basis for understanding the contributions of active properties of dendrites.



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So, you have to have, get this concept of this equivalent cylinder. So again, all this stems from the work of Wilfrid Rall and (23:36), more recently. So, rules governing impedance have been worked out on a particular case, whether the sum of the daughter branches raised to  $3/2$ , so 1.5 power, is equal to that of the parent branch. So here, the systems of branches is an equivalent cylinder resembling a single continuous cable. So, this is the actual cell, we are making it into compartments, you are putting, you know, assigning various  $c$  and  $r$  terms to each compartment and finally, you get an equivalent cylinder resembling a single continuous cable.

So when you have, such a model, it is a starting point in analyzing both synaptic integration and equivalent dendrites. So, integration of synaptic potentials in passive dendrites is non-linear because different synaptic, synapses are conductances, so they interact. So, the rules for understanding the electronic spread and electrotonic spread in dendrites are the basis for understanding the contribution of active properties of dendrites.

So, one thing to be borne in mind is that dendrites also have active conductances, so that adds another layer of complexity when you are modeling. And if you want to do realistic modeling, you have to assign and put in all these terms, whatever we get from experimental physiology has to be added. And then only, your model will replicate or kind of replicate what is happening in the real situation.

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Thank you!

Further readings:

1. Papers by Wilfred Rall and Rinzel
2. Methods in Neuronal Modeling: From Ions to Networks.  
Editors: Christof Koch and Idan Segev. 2<sup>nd</sup> edition. MIT Press, 1998.

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So thank you, and further readings, I strongly, if you are interested in this stuff, I recommend you to checkout Wilfrid Rall and Rinzel - Rall and Rinzel, other like Hodgkin and Rall and Rinzel for cable theory. Go on PubMed, put in Wilfrid Rall and you will get a lot of his original papers. And those of you who like books, I strongly recommend Methods in Neuronal Modeling: From Ions to Networks by Christof Koch and Idan Segev. So, this is available from MIT Press and I think you have copies of it available on the internet.

So, thank you very much, this has been a slightly complex session and, but you need to know all this to realistically model neurons and that is possible. Thank you.